HISTORICAL REVIEW OF ATOMIC FREQUENCY STANDARDS USED IN SPACE SYSTEMS – 10 YEAR UPDATE

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Abstract

A 1996 paper estimated "that the total number of space-borne atomic frequency standards (AFS) is no more than several hundred" [1, p. 24]. The number of atomic frequency standards in space was dominated by the GPS, GLONASS, and Milstar satellite constellations. In this paper, we present an update to the historical review of the AFSs used in space systems. We will briefly review the systems existing in 1996, and add the newer systems (Galileo, GPS IIR and IIF, GLONASS-M, Cassini-Huygens, AEHF, and QZSS) and potential space systems (PARCS, PHARAO, Beidou) using atomic frequency standards. We have estimated that there have been a total of 452 atomic frequency standards launched into orbit for use on communications and scientific payloads. We conclude the paper with a review of the 1996 predictions for future AFSs and discuss the future as seen in 2006.

REVIEW OF 1996 PAPER

This is the 10-year update of a paper **[1]**, by two of the above authors, that described the history of atomic frequency standards in space. A more general introduction to AFSs can be found in the same conference proceedings **[2]**. McCoubrey described molecular and atomic beam methods, buffered gas cell resonance devices, and masers. The requirements of many scientific, military, and navigational missions could only be met with AFSs on satellites. Acronyms and definitions are given after the conclusions section.

GLOBAL POSITIONING SYSTEM (1996)

The first three GPS Block I satellites (also known as Navigation Development Satellites) were each launched with three Rb AFSs on board. The apparent low reliability of early Rb AFSs, together with the better overall performance of cesium AFSs, resulted in the remaining GPS Block I satellites to each carry

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **01 JAN 2007**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Historical Review Of Atomic Frequency Standards Used In Space Systems 10 Year Update**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Boeing Company, Los Angeles, CA 90009, USA**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002029., The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**12**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

four AFSs (three rubidium AFSs and one cesium AFS). The first GPS satellite to fly a cesium AFS was NAVSTAR-4. Further work on the early Rb AFS problems resulted in numerous design improvements. One of the significant design modifications was the temperature controller that was added to the thermal base plate of the rubidium AFSs (first flown on NAVSTAR 7) to maintain the Rb AFS at essentially constant temperature in spite of the fluctuations in the satellite temperature. Each of the GPS Block II/IIA satellites carried two rubidium AFSs and two cesium AFSs.

GLONASS (1996)

The Russian Global Navigation Satellite System (GLONASS) consisted, in 1996, of a constellation of 24 satellites in three orbital planes. The pre-operational phase satellites (Block I: 1982 to 1985) were launched with two "BERYL" rubidium AFSs per satellite. The Block IIa, IIb, and IIc satellites (starting in 1985) carried three "GEM" cesium AFSs **[3]**.

NAVEX (1996)

A navigation experiment (NAVEX) as a part of Spacelab Mission Dl was launched on shuttle flight STS-61A with a FTS 4000 Cs AFS (S/N 168) and an Efratom FRK-H Rubidium AFS (S/N 955). The flight extended from 30 October to 6 November 1985.

MILSTAR (1996)

The Military Strategic and Tactical Relay (Milstar) program is a US military communication satellite system with a digital communication system. It carries several rubidium AFSs onboard. Two Milstar satellites had flown as of 1996. Since then, the full complement of six have been launched and are described below.

GRAVITY PROBE-A (1996)

Gravitational redshift experiments, known as the Gravity Probe-A (GP-A) experiment, were conducted in 1976. A hydrogen maser was launched in a sub-orbital trajectory to an altitude of 10,000 miles by use of a Scout-D rocket system. The flight duration was about 2 hours, during which time the space H-maser clock's frequency variation was measured relative to the frequency of a ground maser clock.

This section reviewed the systems that used atomic frequency standards in space as of 1966, when the original paper was prepared. The paper concluded with a chart showing that approximately 300 atomic frequency standards had been built and launch into space from 1974 to 1996.

NEW AND NEWER SYSTEMS

The atomic frequency standard in the navigation payload has improved over the years, yielding a nearly threefold increase in ranging accuracy over original specifications **[4]**.

This section will discuss new systems that are flying, or will fly, atomic frequency standards. The new systems include Galileo and QZSS and newer systems such as GPS, GLONASS, Milstar, and AEHF. Other interesting space systems will be mentioned, as well as a short but interesting review of company names that have changed in the last 10 years.

GALILEO

Galileo is a joint initiative of the European Commission and the European Space Agency (ESA) for a state-of-the-art global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control. It will probably be inter-operable with GPS and GLONASS, the two other Global Navigation Satellite Systems (GNSS) available today. The fully deployed Galileo system consists of 30 satellites (27 operational and 3 active spares), stationed on three circular medium earth orbits (MEO) at an altitude of 23,222 km with an inclination of 56 degrees to the equator **[5]**.

Atomic clocks represent critical equipment for the satellite navigation system. The Rubidium Atomic Frequency Standard (Rb AFS) and Passive Hydrogen Maser (PHM) are at present the baseline clock technologies for the Galileo navigation payload. According to the present baseline, every satellite will embark two Rb AFSs and two PHMs. The adoption of a "dual technology" for the onboard clocks is dictated by the need to insure a sufficient degree of reliability (technology diversity) and to comply with the Galileo lifetime requirement (12 years). Both developments are based on early studies performed at the Observatory of Neuchâtel from the end of the 1980s and Temex Neuchâtel Time (TNT) since 1995. These studies have been continuously supported by Switzerland within ESA technological programs, especially since the setup of the European GNSS2 program **[5]**.

The activities related to the Galileo System Test Bed (GSTB-V2) experimental satellite, as well as the implementation of the In Orbit Validation phase, are in progress. An experimental satellite (Galileo In-Orbit Validation Element, GIOVE) was launched at the end of 2005 and another will be launched in 2007, to secure the Galileo frequency fillings, to test some of the critical technologies, such as the atomic clocks, to perform experimentation on Galileo signals, and to characterize the MEO environment. GIOVE A was supplied by Surrey Satellite Technologies Ltd. and launched in December 2005 with two Rb AFSs supplied by Temex. Signals were transmitted on 12 January 2006 **[6]**. There will be one PHM and two Rb AFS on board the satellite (GIOVE B) supplied by Galileo Industries **[7]**.

QUASI-ZENITH SATELLITE SYSTEM

Japan's QZSS is a GPS augmentation system in high elliptic orbits and will fly hydrogen masers **[7]** and rubidium and cesium AFSs **[8]**. The hydrogen maser is being developed by the National institute of Information and Communications Technology (NICT) in collaboration with Anritsu Corporation **[9]**. The rubidium and cesium AFSs are built by PerkinElmer and Symmetricom respectively. The first launch is expected in 2008.

CASSINI-HUYGENS MISSION

The Cassini-Huygens mission to Saturn and its moon Titan began with the launch on 15 October 1997 and completed with the Huygens probe's descent to the Titan surface on 14 January 2005 **[10]**. Two Rb AFSs were used on the mission as part of the Doppler wind experiment (DWE). The transmitter ultrastable oscillator (TUSO) was on the Huygens probe and the receiver ultrastable oscillator (RUSO) was on the Cassini orbiter. The Rb AFSs were built by Daimler-Benz Aerospace, with a space-qualified rubidium oscillator physics package supplied by Ball Efratom Elektronik GmbH **[11]**. The goal of the DWE was to measure wind velocities in Titan's atmosphere **[12]**.

GPS IIR AND IIF

The GPS IIR (R for replenishment or replacement) and IIF (F for follow-on or future) systems are described in this section. The original article **[1**, Appendix A**]** indicated the expected number of rubidium and cesium clocks on the IIR and IIF satellite systems. The actual complements of cesium and rubidium AFSs are different, as explained below.

GPS IIR: The first GPS IIR satellite was launched in 1997. The GPS IIR satellite uses three rubidium AFSs built by PerkinElmer **[13]**. The most recent GPS IIR launch was 17 November 2006.

GPS IIF: The contract for GPS IIF was awarded in 1996. The GPS IIF satellites are expected to launch with two rubidium AFSs and one cesium AFS. The Rb AFS is built by PerkinElmer and has better performance than the GPS IIR Rb AFS because of an improved physics package design **[13]**. The cesium AFS is built by Symmetricom. The first GPS IIF launch is expected in 2008

Modernization: The Block IIR-M (M for modernized) satellites add downlink signals and increase output power for more robust signals, but do not affect the number AFSs launched. The last eight of the GPS IIR satellites and all of the GPS IIF satellites will be modernized **[14]**.

GPS III: The GPS III program is the next generation of GPS satellites and control segment. The contract is "expected to be awarded in May or June of 2007" **[15**, p. 18**]**. The largest effort in the United States in new technology space clocks is the Advanced Technology Atomic Frequency Standard (ATAFS) program at the GPS Wing. That program is currently funding efforts at Frequency Electronics, Kernco, and Symmetricom to develop space qualified atomic clocks suitable for use in future GPS satellites. The technologies include rubidium gas cell, CPT maser **[16]**, and optically pumped cesium **[17]**.

GLONASS

GLONASS: The Russian global navigation satellite system (GLONASS or global'naya navigatsionnay sputnikovaya sistema) had over 24 satellites in orbit at the time of our original paper in 1996, but has since dropped to a low of "seven operational satellites" **[14**, p. 28**]**. A policy decision in 2001 led the way for a return to a full 24 satellite configuration by 2011 **[18]**. The GLONASS system will be comprised of the original GLONASS satellites with a life of up to 3 years, the current build of GLONASS-M satellites with a lifetime of 7 years, and the forthcoming GLONASS-K satellites with a life of 10 years **[19]**.

GLONASS-M: There were several reasons for the short mission durations and one was "the quality of on-board atomic clocks and system timekeeping ... contributed to the problem" **[14**, p. 29**]**. The 12 modernized satellites (GLONASS-M, also called Uragan-M) are being manufactured by Reshetnev Applied Mechanics Research and Production Association **[14**, p. 29**]**. The first GLONASS-M satellite was launched in 2003 and there are now four in orbit. The Uragan-M satellites have three cesium AFSs developed by the Institute of Radionavigation and Time **[20**, p. 1164**]**. They are expected to achieve one-day stability of $1\text{x}10^{-13}$ by maintaining the AFS's temperature stability to ±1 degree C **[18**, p. 42**]**.

GLONASS-K: The lighter-weight GLONASS-K (Uragan-K) satellites are expected to have both rubidium and cesium AFSs **[21**, p. 160**]**. The first GLONASS-K is expected to launch in 2008 **[14]**.

MILSTAR AND AEHF

The first Milstar satellite was launched in 1994 with crystal oscillators. Rb AFSs were introduced with the second launch in 1995 through the launch of the sixth Milstar satellite in 2003. They carried either three or four rubidium AFSs built by FEI. The follow-on program to Milstar is the Advanced EHF (AEHF) program and will fly three rubidium AFSs built by FEI. None of the AEHF satellites have been launched.

POTENTIAL SPACE SYSTEMS OF INTEREST

PARCS: The cesium clock in the primary atomic clock in space (PARCS) mission was designed with a 75-cm-long Ramsey cavity and is intended for various experiments in the low gravity of the International Space Station (ISS). PARCS is no longer scheduled for use on the ISS **[22]**.

PHARAO: The *Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite* (PHARAO) project is an AFS for the ESA-supported Atomic Clock Ensemble in Space (ACES) mission. It was intended to be installed on the International Space Station to study a laser-cooled cesium clock in a microgravity environment **[23]**.

BEIDOU/COMPASS: China's Beidou (a.k.a. Compass) satellite positioning system launched two navigation test satellites into geostationary orbit in October and December 2000 and a third in May 2003. The satellites do not contain atomic frequency standards **[24]**. However, a recent news article stated:

> China has ordered 18-20 rubidium atomic clocks, a key component of satellite navigation systems. However, this is nowhere near enough to create a global constellation, which requires at least 21 satellites, especially since there are usually multiple clocks per satellite ... **[25]**

It is reported that the Beidou satellite system will provide two levels of service. "The Open Service is designed to provide users with positioning accuracy within 10 meters, velocity accuracy with 0.2 meter per second and timing accuracy within 50 nanoseconds" **[26]**.

COMPANY TRANSITIONS IN THE LAST 10 YEARS

Several companies were mentioned in the original paper **[1]** that have since changed names by merger or acquisition. Boeing purchased the space assets of Rockwell International in 1996 and those of Hughes Aircraft Company in 2001. TRW was purchased by Northup Grumman in 2002. Frequency and Time Systems (FTS) and Efratom became Datum in the 1990s and merged with Symmetricom in 2002. EG&G purchased, and took the name of, PerkinElmer in 1999. Frequency Electronics (FEI), Kernco, Lockheed, and NRL have remained the same.

This section discussed new systems that are using, or will use, atomic frequency standards and ended with a review of company names that have changed in the last 10 years. The next section will summarize our estimate of the number of clocks in space.

ATOMIC CLOCKS CURRENTLY IN SPACE

This study counted the number of atomic frequency standards that have been launched in the last 10 years and appended it to the chart that was presented in the original paper **[1]**. The results are shown in Figure 1.

Figure 1 shows that there have been approximately 452 AFSs launched since the first two in 1974, and about 132 AFSs have been launched in the last 10 years. This does not include the AFSs associated with the launch failures of the first GPS IIR satellite (1997) or the third Milstar satellite (1999). We say approximately, because this study attempted to quantify the number of atomic clocks that have been launched into orbit. We may have missed a few. Please use this as a guide to, maybe, a minimum, but not an absolute number of, the number of atomic clocks that have been launched into space.

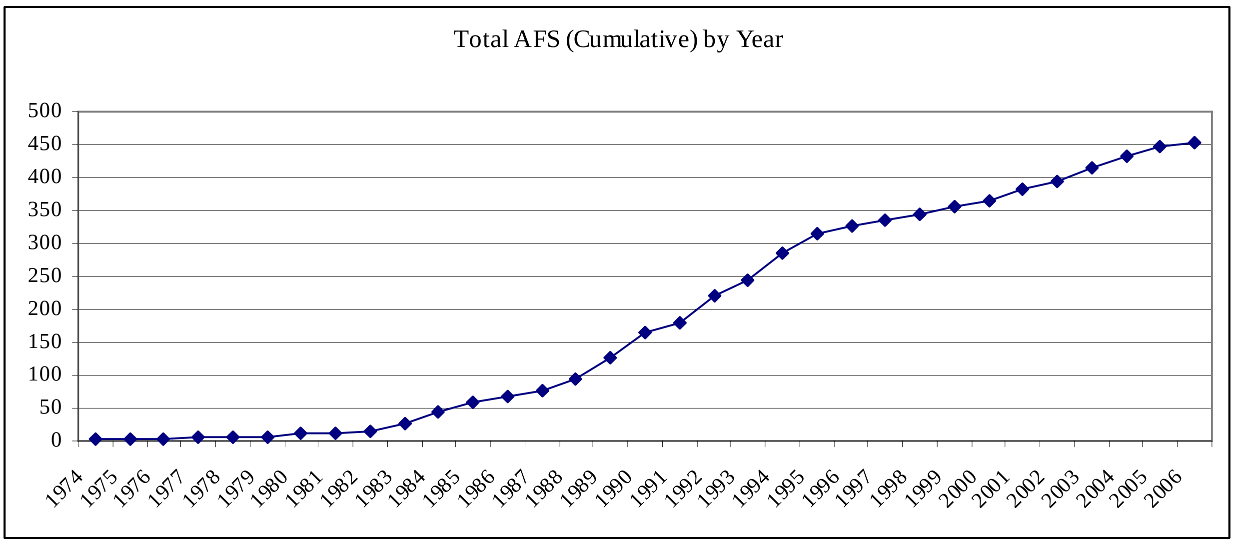

Figure 1. Summary chart of all AFSs in space (cumulative) by year.

The late 1980s and early 1990s saw an average of 26 AFSs per year – this was the GPS and GLONASS system build-up phase. The last 10 years saw an average of 13 AFSs per year – the system replenishment stage. We expect the launch rate of AFSs to increase to about 25 AFSs per year, especially as Galileo and GLONASS build up to their full constellation.

THE FUTURE OF ATOMIC CLOCKS IN SPACE

The original 1996 paper [1] had a section entitled **Future Space Standards**. We thought it would be good to pause and reflect on what was mentioned in 1996, and how the future of AFSs looks in 2006.

REVIEW OF 1996 PREDICTIONS

The original 1996 paper **[1]** made the following predictions about the future of atomic standards. Some words of this quote are in bold – they have been emphasized in this paper for further discussion below:

> To a large measure the remarkable improvement in the performance of the AFSs over the last two decades is in large part due to the excellent progress in the electronics-both performance and packaging. Many manufacturers have introduced sub-miniature Rubidium AFSs into the market whose absolute performance and performance per dollar is very impressive. **This miniaturization will strongly impact the development of Space Rubidium AFSs.** Another area where there is considerable promise is the development of "smart clocks." Conceptually this would require additional sensors and servos to sense and correct environmental effects and other variations–microwave power level, magnetic field, and electron multiplier gain, are just a few. **This could nearly eliminate the effects of temperature and magnetic field changes resulting in excellent long-term stability.** For the immediate future the traditional Rubidium AFSs and Cesium AFSs of the present design physics packages is expected to be used, albeit with significantly improved performance and reliability. However, there are a number of research and development efforts in the area of new types of standards (i) **optically pumped Cs AFSs:** Optical pumping, state selection and detection will be done using solid state diode lasers. This would eliminate the use of bulky "A" and "B" magnets in the physics package. This will result in lighter beam tubes, improved efficiency and better performance. However, laser diode frequency must be "locked." Temperature of the diode laser has to be controlled to a very high degree. (ii) **Diode laser pumped Rubidium AFSs:** Replacing the Rb discharge lamp with a diode laser tuned to the correct transition frequency offers substantial simplification in the design of the physics package in the Rubidium AFSs. The diode laser can optically pump with nearly 100% efficiency thereby substantially improving the SNR (Signal-to-noise ratio) of the microwave clock signal. This would eliminate the need for the Rb 85 filter cell and also the parasitic effects of the radio frequency used in the discharge lamp. Theoretically, a factor of 100 improvement over the existing design should be realizable. Ongoing experiments show that the light shift effects of the diode laser are very significant. Diode laser frequency has to be "locked." Very encouraging results have started to appear in this area. **[1**, p, 29, bold added, original references have been removed for clarity**]**

The subminiature Rb designs that have changed the commercial atomic frequency standard market dramatically have had very little effect on space rubidium clocks. The reason is simply that the largest customer for space-qualified Rb clocks is GPS. GPS needs the best performance the clock is capable of providing. So far, the market for a lower-performing space Rb has not developed.

The smart clock technology, which adds additional servos to greatly reduce environmental effects in atomic clocks, continues to be used in cesium clocks and to a lesser extent in commercial rubidium clocks. There has been relatively little change in the approach over the last decade.

Optically pumped cesium is close to reality for space, but still isn't quite here. While laboratory devices such as NIST-7 have worked well, the issue for space and commercial devices is the availability of suitable diode lasers. The telecomm industry shifted laser frequency to 1550 Angstroms. With no demand for large-scale production quantities of diodes at cesium wavelengths, the availability dropped dramatically. At this writing, there are European sources for diodes, but the reliability and radiation hardness of those devices is still being investigated. Symmetricom has a contract from the GPS Wing to develop a flight version of the clock with delivery scheduled for 2008 **[17]**. While a commercial

derivative is possible, no plans to build one have been publicly announced. In Europe, the Observatory of Neuchâtel **[27]** and Thales **[28]** have also reported work in optically pumped cesium for space.

There has been some work in the area of optically pumped Rb clocks in the last 10 years **[29,30]**. While light shift and laser noise are still issues, the bulk of the new work in small clocks has been in the Coherent Population Trapping (CPT) technology. Kernco **[16]** has demonstrated a low power clock with stability comparable to traditional gas cell clocks.

2006 PREDICTIONS

The largest effort in the United States in new-technology space clocks is the Advanced Technology Atomic Frequency Standard (ATAFS) program at the GPS Wing. That program is currently funding efforts at Frequency Electronics, Kernco, and Symmetricom to develop space-qualified atomic clocks suitable for use in future GPS satellites. The technologies include rubidium gas cell, CPT maser [16], and optically pumped cesium **[17]**.

CPT clocks continue to be a promising technology area for space and ground. The DARPA Chip Scale Atomic Clock (CSAC) program has lead to several promising devices. While the future of these specific clocks remains to be seen, the technology developed under the program has been exceptional. It could be the basis for less expensive space clocks with moderate performance levels. A major factor in acceptance of these clocks in space programs now using crystal oscillators will be the demonstrated reliability of ground clocks of similar design.

Another device that has shown amazing resilience over the past half century is the hydrogen maser. Galileo **[7]** and QZSS **[8,9]** each plan to use a maser as their high performance space clock. In the West, hydrogen masers have been the reference clocks for major timing laboratories since the 1960's. However, their large size, weight, and power, along with reputation for finicky reliability, have dogged the maser as a space clock. NRL led a program for GPS in the 1980's to make a space-qualified maser. While the program produced a solid engineering model, the clocks never reached production. Similarly, Russia, long recognized as an international leader in maser technology, was thought to have space designs, but never flew masers for their GLONASS program. The Galileo and QZSS masers have rekindled interest for space masers. How far that interest progresses will likely depend on how well these masers perform in space.

Trapped ion, optical, and cold atom clocks are currently a rapidly developing area in science. At their present stage of development, they are still laboratory devices. To be viable candidates for space applications, considerable engineering will have to be done as the science progresses. While several devices have been proposed and built as space experiments **[22,23,31,32]**, none has yet progressed to the point of production for major civil or military programs.

CONCLUSIONS

A 1996 paper estimated "that the total number of space-borne atomic frequency standards (AFS) is no more than several hundred" **[1**, p. 24**]**. The number of atomic frequency standards in space was dominated by the GPS, GLONASS, and Milstar satellite constellations. In this paper, we presented an update to the historical review of the AFSs used in space systems. We reviewed the systems existing in 1996, and add the newer systems (Galileo, GPS IIR and IIF, GLONASS-M, Cassini-Huygens, AEHF, and QZSS) and potential space systems (PARCS and PHARAO) using atomic frequency standards.

Interestingly, the only hydrogen maser used in space (Gravity Probe-A) was 30 years ago. We have estimated that there have been a total of 452 atomic frequency standards launched into orbit for use on communications and scientific payloads. We concluded the paper with a review of the 1996 predictions for future AFSs and discuss the future as seen in 2006.

ACKNOWLEDGMENTS AND DISCLAIMER

Several experts in the atomic frequency standard field were consulted for this paper, especially the section on 2006 predictions. The authors would like to thank Peter Cash, Bernardo Jaduszliwer, Bob Kern, Robert Lutwak, John Prestage, Bill Riley, and John Vaccaro.

This study attempted to quantify the number of atomic clocks that have been launched into orbit. We may have missed a few. There may be some clocks that were launched and never turned on. Please use this as a guide to, not an absolute number of, the number of atomic clocks in space. Parts of this paper are the personal opinions of the authors and do not necessarily reflect the opinions of other persons or organizations.

ACRONYMS AND DEFINITIONS

AEHF	Advance extremely high frequency; satellite; follow-on to Milstar satellite
AFS	Atomic frequency standard
ATAFS	Advanced Technology Atomic Frequency Standard
Cs AFS	Cesium atomic frequency standard
CPT	Coherent Population Trapping
DARPA	Defense Advanced Research Projects Agency
ESA	European Space Agency
Galileo	A joint initiative of the European Commission and the European Space Agency (ESA) for a state-of-the-art global navigation satellite system, providing a highly accurate, guaranteed global positioning service under civilian control.
GIOVE	Galileo In-Orbit Validation Element; two satellites identified as A and B
GLONASS	Global Navigation Satellite System; Russian
GP-A	Gravity probe A; gravitational redshift experiment resulting from the difference in the Newtonian gravitation potential between the space clock and the ground clock is measured.
GPS	Global positioning system, USA
GSTB	Galileo System Test Bed
Milstar	Military strategic and tactical relay satellite
PHM	Passive hydrogen maser
MEO	Medium earth orbit
PARCS	Primary atomic reference clock in space
PHARAO	*Projet d'Horloge Atomique par Refroidissement d'Atomes en Orbite*
QZSS	Quasi-zenith satellite system; a GPS augmentation system, Japan
Rb AFS	Rubidium atomic frequency standard

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